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Abstract

Hydrocarbon fuels are being considered for many boost applications due to their higher energy densities compared with hydrogen. RP-1 has been the standard hydrocarbon fuel for the past several decades. However, there are a great variety of potential hydrocarbon molecules, ranging from the common to the exotic, which can also be used as fuels. These compounds have potentially higher energy content compared to RP-1 which could lead to engine performance gains. However, we are also looking at other properties, such as regenerative cooling capability, coking and corrosion behavior, and lubricity. All of these properties could provide overall system advantages. AFRL/PRS has undertaken the task of examining the potential capabilities of a wide range of these hydrocarbon molecules to determine their overall performance as a rocket fuel.

In this paper, we will discuss the initial stages of combustion performance testing of these potential new fuels. The initial sets of fuels that are being characterized include several common hydrocarbon propellants such as RP-1, JP-7, JP-8, JP-10, and Butane in a sub-scale, uni-element combustor. In order to ascertain differences between injectors, several injector styles will be tested with these fuels and the results will be examined to determine appropriate test conditions to make the most accurate assessment.

Initial results indicate that this first set of fuels behave as expected. C* efficiency was relatively high, typically exceeding 95%. The variation between fuels (with the same injector) was also relatively low, indicating that the injector and chamber design are suitable for performance testing with a wide variety of fuels.

Introduction

RP-1 has been the standard liquid hydrocarbon rocket fuel for the past 40 years. A re-exploration of currently existing hydrocarbons has led to the realization that other compounds may provide the opportunity for improved engine performance, improved system performance, or both. In order to ascertain which molecules have the potential to be high performance rocket fuels, a variety of tests need to be conducted. In addition to the combustion hot-fire performance work presented in this paper, studies are currently underway at the AFRL/Edwards Research site to examine the toxicity, lubricity, coking, corrosion, and cooling characteristics of these potential advanced fuels.

As a precursor to the testing of these alternative hydrocarbon fuels, the Air Force Research Laboratory in conjunction with NASA-Glenn Research Center has begun making measurements of a variety of commonly available, hydrocarbon fuels in order to establish a representative baseline from which the new fuels can be compared. This testing involves both combustion performance testing, as well as characterization of the coking properties of these propellants. In this initial round of testing, the combustion performance of RP-1, JP-7, JP-8, JP-10, and Butane were tested at AFRL in the sub-scale uni-element combustor test facility (EC-1). A schematic of this combustion chamber as well as a picture of the facility are shown in Figure 1. This GOX/HC 100-400 lbf workhorse hardware has a heat sink chamber and is capable of being quickly modified to vary the chamber length, injector, and fuel. This combustor can also be

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equipped with a section granting optical access to the combustion chamber. This feature, however, was not utilized in this set of experiments. The primary figure of merit used in this study was C* (and C* efficiency), however, I_{sp} measurements were also made during some of the firings.

It should be noted that we did not expect to observe (nor did we find) any surprises in the data acquired for this paper. The performance of the various fuels was as expected. The goal of the present work was to establish a consistent baseline and to show that the results from our combustion chamber are highly repeatable. In effect, this work serves as a precursor to the testing a variety of alternative hydrocarbon fuels and understanding any sensitivities of the test hardware to the fuels that will be studied.

The injectors selected for these tests were a GOX-centered, swirl injector developed by Sierra Engineering under an MDA SBIR. As the name implies, these injectors direct the gaseous oxidizer through the center of the element while the liquid fuel is directed along the wall producing a swirling, liquid film. These injectors are different from the swirl coaxial elements previously demonstrated by Aerojet (Muss and Meagher, 1988) and other engine manufacturers. These prior designs were primarily for liquid oxidizer/gaseous fuel systems and shroud the liquid oxidizer core with gaseous fuel. Conceptually, the current injectors are similar to the elements used in Russian flight engines and offer the potential for high thrust per element and low fabrication cost. The performance and details of the design of these injectors has been reported in Cohn *et al.* (2003) and Muss *et al.* (2003).

Results from two of the injectors developed under the MDA program will be reported in this paper. The converging style injector (Figure 2a) has been extensively tested with all of the fuels listed above. This injector has demonstrated high C* efficiency (greater than 95%) for a variety of chamber conditions and fuels. The primary feature of this injector is a small chamber in which the propellants premix before entering the main combustion chamber. The diverging style shown in Figure 2b injects fuel downstream of a sudden expansion. Note that the injector used for the tests in this paper feature an expansion angle, $\theta = 0°$. In this case, the propellants do not have the opportunity to significantly pre-mix before entering the combustion chamber.

Experimental Setup

All combustion tests were performed in the EC-1 uni-element combustor test facility located at the the AFRL/Edwards research site. A copper, heat-sink, combustor, shown in Figure 1, was used for all of the testing. Testing was conducted at chamber pressures ranging from 300-1000 psia with the bulk of the testing conducted at nominally 350, 500, and 750 psia. For each test condition, a Mixture Ratio sweep was conducted for each of the fuels. Typically this sweep included the optimum C* condition as well as ±10%, and ±20% of optimum. Repeats were conducted in order to ascertain the stability of the system.

The engine in the EC-1 facility sits on top of a highly accurate thrust stand designed and manufactured by IAS. This stand has an in-frame calibration system which allows for calibrations to be easily performed before each test day. Center-line pulls have been conducted on this system and the resulting estimated error of the system is less than 0.15%.

Typical engine chamber length for the testing reported here is L'= 8.375 in. However, limited testing at shorter chamber lengths was conducted to better understand the effect of mixing efficiency for these injectors. The combustion chamber has a 2 in x 2 in interior cross section. With the .45 in nominal throat, this yields a contraction ratio of 25.2. This is significantly larger than the contraction ratio of typical rocket engines; however, this large contraction ratio is necessary in order to allow sufficient optical access while maintaining reasonable propellant flow rates. The characteristic length of this chamber, L*, was 15.1 ft. This is also greater than normally found in typical rocket engines. These values and quantities should favor more complete combustion of the fuel which will need to be included in the overall analysis of these fuels. The effect of the variation of these parameters will be examined in future efforts.

Typically, a minimum of ½ seconds of steady state firing time was established for each test. This proved sufficient time to acquire the necessary data. Typical data acquisition rate was 1 KHz. All of the data reported are the average of 0.4 s of data. Thus 400 samples are averaged for the data reported. This greatly reduces the magnitude of any random errors.

The nozzle utilized has a physical expansion ratio of 1.87. This will greatly decrease the thrust produced by the engine compared to optimal. However, the same nozzle design, with nominally the same nozzle diameter, was used in all testing. This

allows for the direct comparisons of I_{sp} results to be justified.

A detailed uncertainty analysis was performed in order to understand the magnitude of the uncertainty in these measurements. As AFRL progresses through our analysis of alternative hydrocarbon fuels, this knowledge will be extremely important in selecting appropriate alternative fuels and to understand what measured differences between the fuels are meaningful.

Propellant flow-rates were established and measured by cavitating venturis/sonic nozzles. The liquid venturis were calibrated in-house with water, RP-1, and JP-10. The calibrations were then compared with each other, after correcting for vapor pressure and density. Typically, these three calibrations compared within 1%. The sonic nozzles were also calibrated in-house using GN2 to develop the appropriate discharge coefficient for the nozzle. Spot-check calibrations with GOX provided suitable confidence in these results. Uncertainty estimates for the liquid venturi flow rates was less than 1%. Primarily, this uncertainty is the result of the process of converting results between the different fluid media. Estimate for the gas-side flow rate uncertainty was 0.5%. Both of these values can be reduced by performing all calibrations with the requisite propellant.

The chamber pressure transducers used for these experiments were accurate to 0.05% of their full-scale value. Since measurements were typically made at ¼ of their full-scale output, the typical pressure measurement uncertainty was 0.20%. Another significant contributor to the uncertainty is the nozzle diameter. Combined in this uncertainty is the accuracy of the measurement of the nozzle as well as the change in the nozzle diameter as it heats during the test. It was estimated that this error was less than 0.002 in. Using the nominal nozzle diameter of 0.45 in, this yields an uncertainty of 0.44%.

Using these values, we estimate that the uncertainty of the I_{sp} measurements is less than 0.50% and the uncertainty for C* measurements is 1.0%. These uncertainties are dominated by the uncertainty of the throat diameter and the propellant flow rate uncertainty. The butane data that is presented is from an older set of experiments. The uncertainty of those measurements is approximately double those listed above for the RP-1 and JP-10 data.

Results and Discussion

Figure 3 shows a sample plot of a typical firing of the uni-element hardware. It is apparent from this plot that a solid steady state exists. For this firing, chamber pressure was approximately 760 psig. Both the fuel and oxidizer venturi were choked with a pressure recovery (venturi downstream pressure divided by venturi upstream pressure) of 75% and 77% respectively. The pressure in all feed lines was very stable. In fact, the standard deviation over a 0.4 s time period for chamber pressure, fuel venturi inlet pressure, and oxidizer venturi inlet pressure were less than 0.6%, 0.25%, and 0.078% respectively. The pressure fluctuations seen after 4.5 s are a result of the engine purges. Figure 4 shows two examples of the resulting engine plumes. One of the plumes is a fuel rich case with a distinct orange plume while the second is an oxidizer rich case with a clear-blue plume. Mach diamonds are clearly visible in the oxidizer rich case.

Figure 5 shows plots of the variation of C* with mixture ratio for Butane, RP-1, and JP-10 for three different nominal pressure conditions; 350 psia, 500 psia, and 750 psia. The actual pressure of the points shown in this chart are ±10% of the nominal value. Figure 5a shows the results for 350 psia chamber pressure. This chart also shows the theoretical C* value and 95% of the theoretical C* value for all three fuels in addition to the experimentally generated data. Generally, the converging injector shows values in excess of the 95% curve for all three fuels. However, the diverging injector has distinctly lower performance compared to the converging injector.

Figure 5b displays the mixture ratio variation of the three fuels for the 500 psi case. Similar to the 350 psi results, the diverging injector does not perform as well as the converger. Within the mixture ratio range studied, we do not see experimental evidence of the drop in characteristic velocity as we move to either side of the optimum value. However, within the mixture ratio range examined, this difference is not significant and could easily be masked by other effects. Tests at larger and smaller MRs need to be conducted to see the decrease in C*.

Figure 5c displays the results for the 750 psi chamber pressure conditions. It is apparent that the increase in chamber pressure has resulted in an increase in C*. This is more apparent in Figure 5d which compares the converging injector with RP-1 used as the fuel at the three pressure levels. In the mixture ratio range from 2 to 2.5, the increase in C* is

apparent. At the high end, the gap appears to close. This may be due to an increase in the velocity of the gaseous oxygen core flow at the higher mixture ratios resulting in better mixing of the fuel and oxidizer.

Figure 6 presents the C* efficiency for the converging and diverging injectors. It is apparent that both of the injectors have efficiencies greater than approximately 90% for all of the fuels. In general, the converging injector achieved C* efficiencies in excess of 95% for all three fuels tested, while the diverger performance was slightly lower. Because of the wide range of fluid properties between these fuels, including a density (specific gravity) variation of nearly a factor of two ($S.G._{Butane} = 0.58$, $S.G._{JP-10} = 0.93$), a vapor pressure variation of more than a factor of 100 ($P_{vap,butane} = 30$ psi, $P_{vap,RP-1} = 0.25$ psi, and a difference in critical pressures of nearly a factor of two ($P_{crit,RP-1} = 315$ psi, $P_{crit,JP-10}=542$ psi and the consistently high performance, we feel that this converging injector is an excellent choice for the initial evaluation of new fuels.

It should not be construed from this work that all diverging injector styles have lower performance compared to the converging styles. We have performed limited testing of several modified diverging style injectors which had excellent performance, some rivaling the performance of the converging element reported here. However, the testing was not extensive enough to report in this paper.

The very high combustion efficiencies seen in these results are definitely affected by the long L* of the chamber. Some limited testing was conducted with butane to ascertain the effect on C* of reducing the chamber length. It was found that a 21% reduction in L* resulted in a 2-4% reduction in C* when using the converging injector, however, when a diverging type element was utilized, C* dropped by over 10%. This result is not incredibly surprising since the converging injector premixes the fuel and oxidizer before they reach the combustion chamber. Only a small number of samples were acquired and more extensive testing of this phenomenon will occur in the near future.

During testing, the specific impulses of the fuels were also acquired. Because of the high accuracy of the thrust stand installed in EC-1, I_{sp} measurements have less uncertainty compared to c* measurements since the nozzle area is not required for I_{sp}. However, when comparing to the ideal values, the actual nozzle expansion ratio must be known. The results of the I_{sp} measurements can be seen in Figure 7. For the mixture ratio range studied, the measured I_{sp} was nearly constant for each fuel. However, the measured specific impulse of JP-10 was larger than the measured specific impulse for RP-1. This result was quite unexpected and the cause still needs to be determined.

Conclusions

Several common hydrocarbon fuels have been studied as a precursor to performance testing of several alternative hydrocarbon fuels. Both the current set of tests, as well as the future testing, measured the combustion performance of these common fuels using C* and I_{sp} as primary and secondary figures of merit respectively.

A GOX-centered, swirl injector was used for the testing. This injector features a gaseous oxidizer core surrounded by the liquid fuel. These injectors are relatively simple to manufacture and offer the promise of high thrust per element, which will reduce parts count and overall costs in full scale rocket engines. For the purposes of fuels comparison, these elements have demonstrated that they are relatively insensitive to fuel properties and demonstrate high performance over a wide range of chamber pressures. Performance in the uni-element subscale chamber was very good with ηc^* typically exceeding 95%.

This set of test results verifies the test concept for future studies of alternative hydrocarbon fuels. We have verified that the injector and combustor are relatively insensitive to fuel properties over a broad range. Thus, a wide range of new fuels can be tested under nearly identical conditions using the same injector and combustor. This will help reduce uncertainty and allow for a direct, meaningful comparison of the performance of the new fuels. Any changes in performance and performance efficiency of these advanced fuels are likely the result of the fuels being studied.

Work is also ongoing within the propulsion directorate at AFRL in the development of a 1500 lb_f multi-element combustor which utilizes the same injectors used in this study. This will allow multi-element effects of the alternative fuels to be studied.

It should be note that fuel performance is just one area that needs to be studied in order for these high performing molecules to become useful as rocket fuels. In conjunction with the combustion performance testing, efforts are underway to examine

the toxicity, lubricity, corrosion, and cooling characteristics of these fuels.

Acknowledgements

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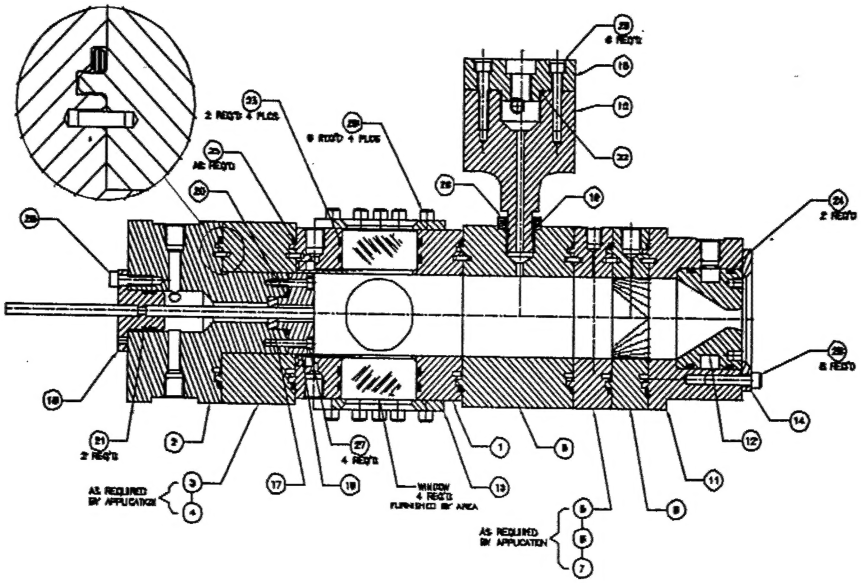
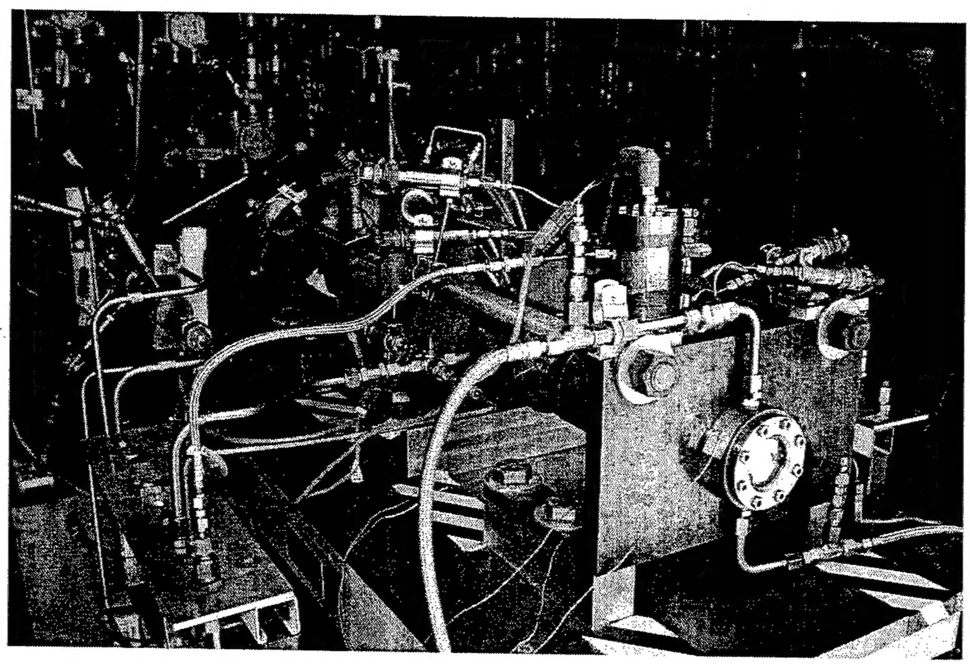


(a)



(b)

Figure 1: Schematic (a) and picture (b) of EC-1 uni-element combustor.

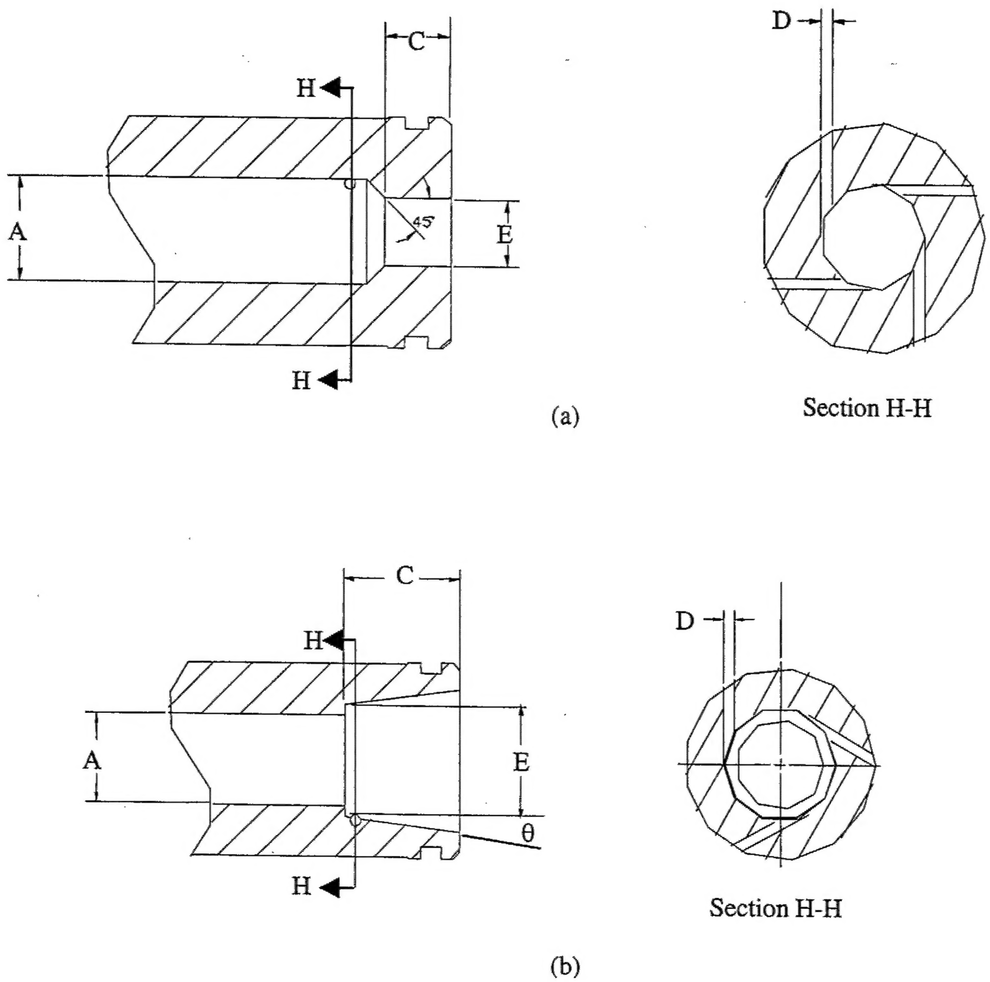


Figure 2: Schematic of converging (a) and diverging (b) injector.

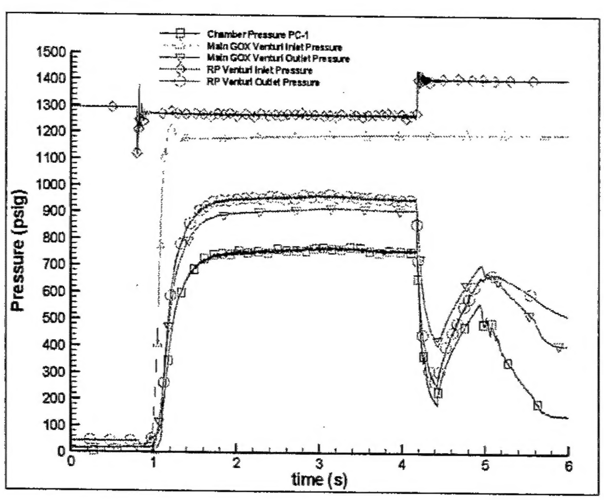


Figure 3: Sample pressure plot for Hydrocarbon fuel testing.

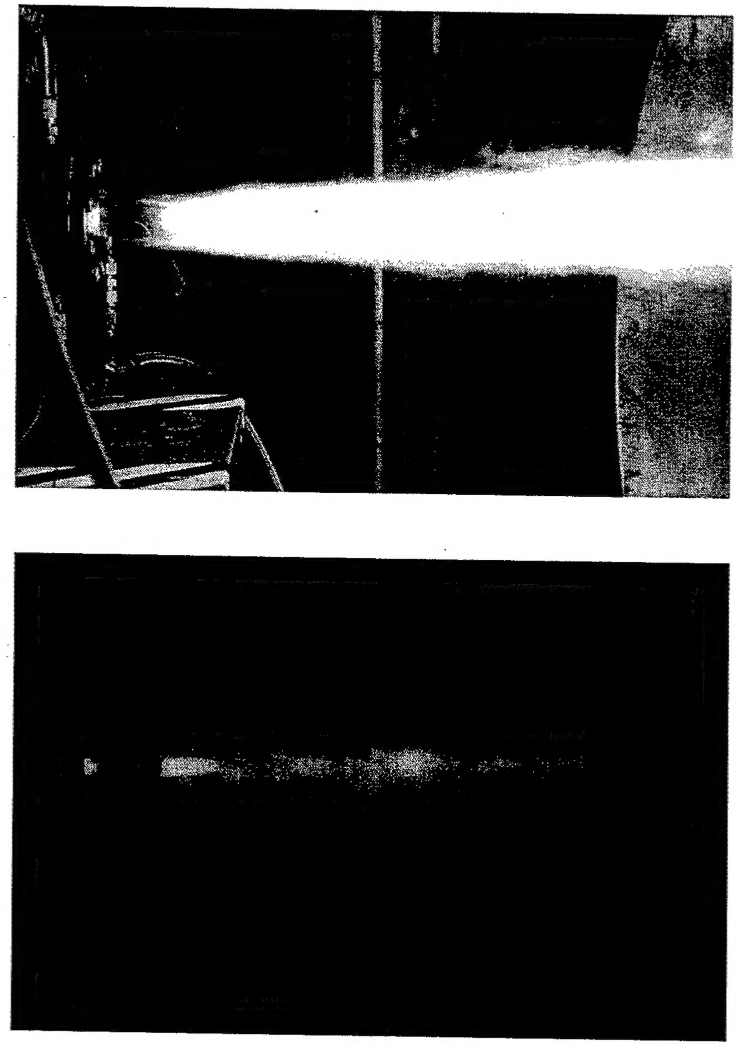


Figure 4: Examples of fuel rich (top) and oxidizer rich (bottom) engine plumes.

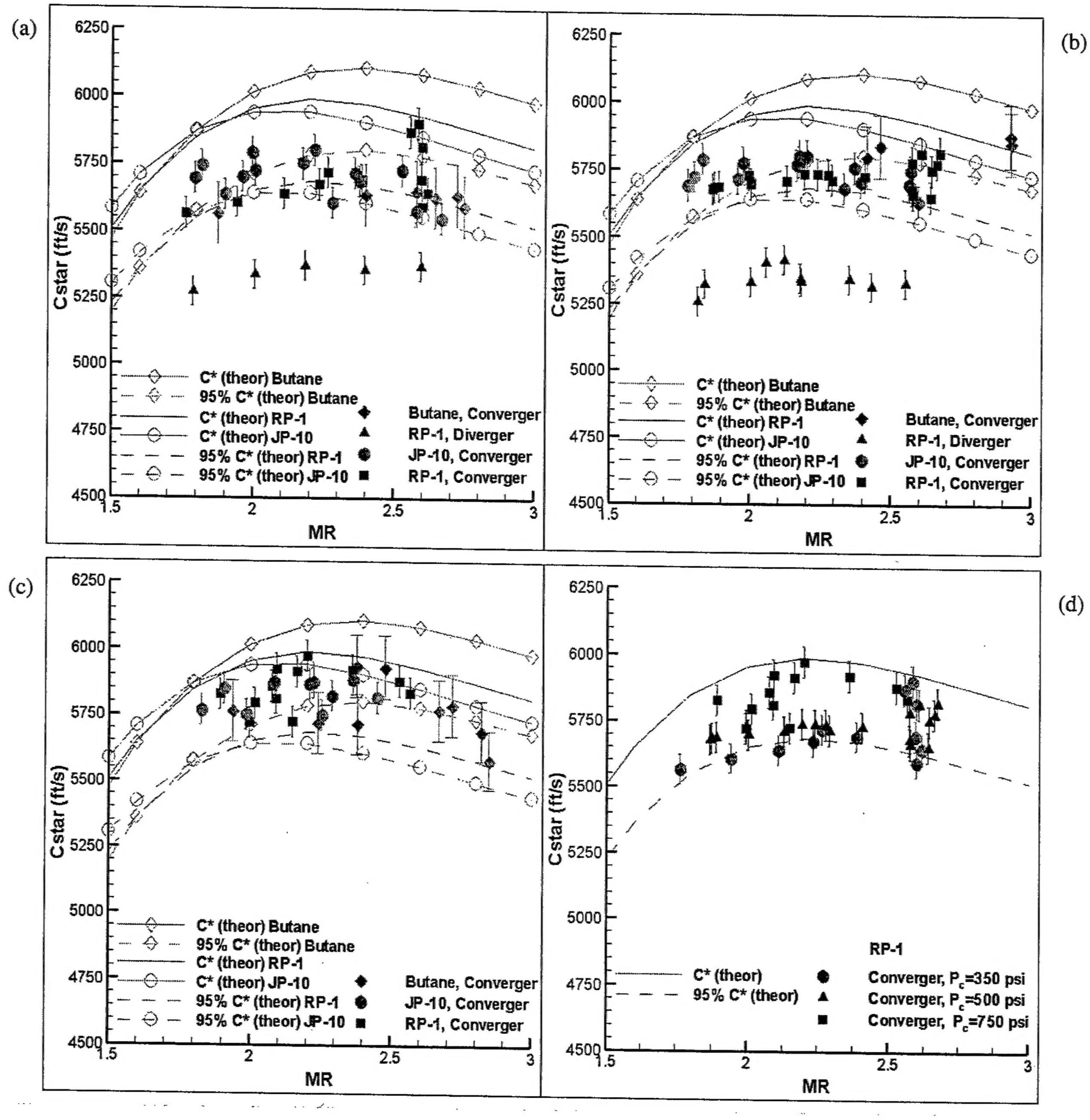


Figure 5: C* variation with mixture ratio for converging and diverging injectors. (a) 350 psi. (b) 500 psi. (c) 750 psi. (d) Comparison of converging injector with RP-1 at 3 chamber pressures.

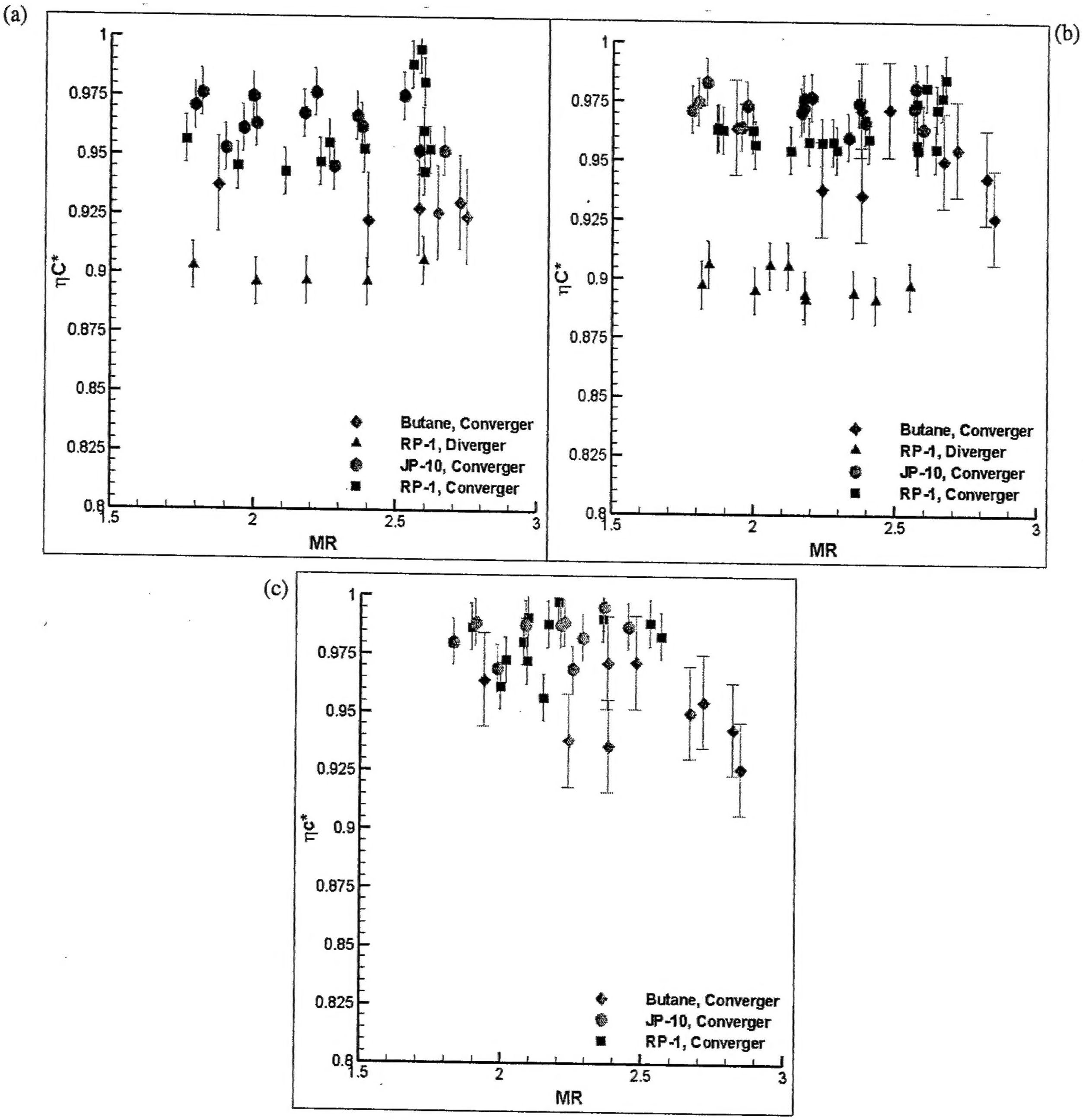


Figure 6: C* effeciency with mixture ratio for converging and diverging injectors. (a) 350 psi. (b) 500 psi. (c) 750 psi.

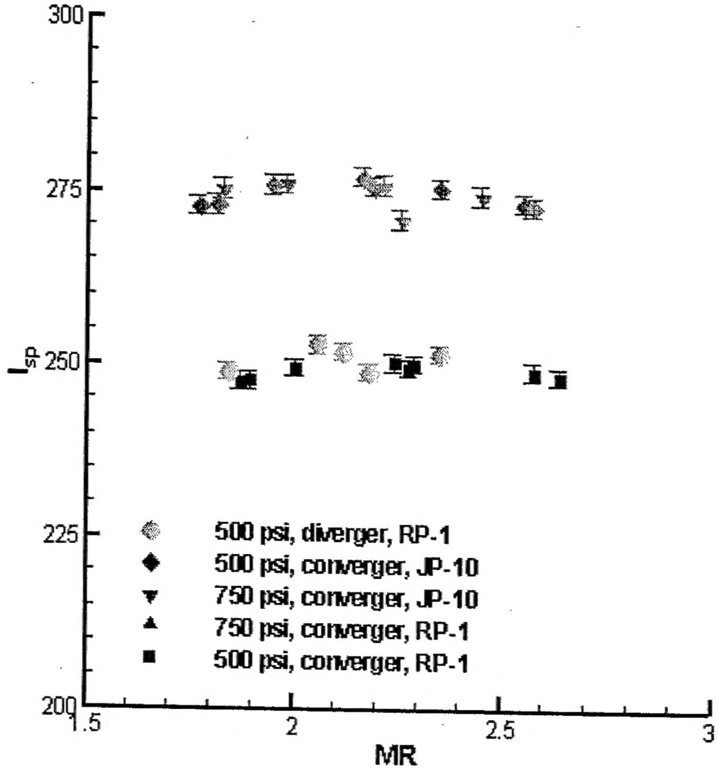


Figure 7: Isp variation with mixture ratio for RP-1 and JP-10.